Two-photon exchange in elastic and inelastic electron-proton scattering

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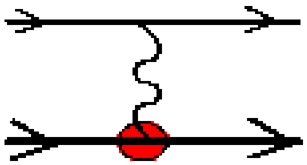
- 2γ exchange in $ep \to ep$, intermediate nucleon and Δ
- 2γ exchange in $ep \to e\Delta$
- Conclusion

Motivation

Extracting nucleon e-m form factors $G_{E,M}(Q^2)$ from

$$ep \longrightarrow ep$$



Born: one–photon exchange (traditional description)

$$\tau = \frac{Q^2}{4m_N^2} \qquad \frac{1}{\epsilon} = 1 + 2(1+\tau)tg^2\frac{\theta}{2}$$

Rosenbluth method (unpolarised scattering)

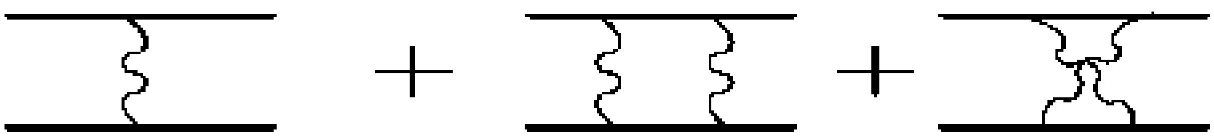
$$d\sigma_{1\gamma} \sim G_M^2 + \frac{\epsilon}{\tau}G_E^2$$

Sensitive to small higher-order corrections $\sim \epsilon$

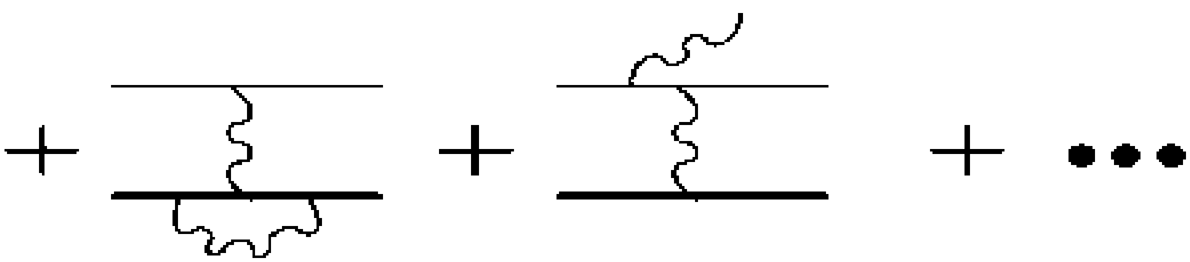
Polarisation transfer method (polarised scattering)

$$\frac{P_T}{P_L} \sim -\sqrt{\frac{2\epsilon}{\tau(1+\epsilon)}}\frac{G_E}{G_M}$$

Insensitive to higher-order corrections

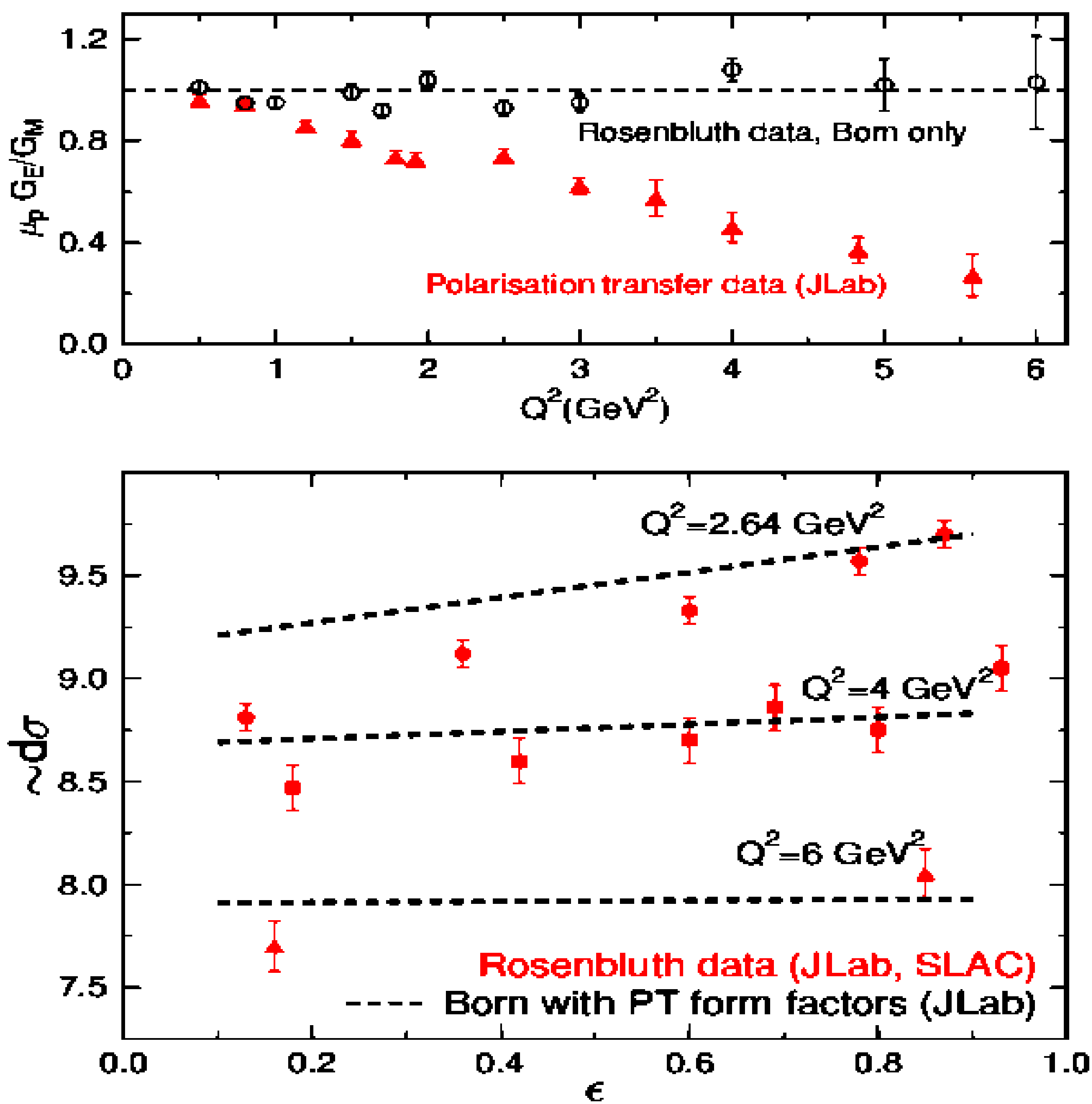


Two–photon exchange



Other radiative corrections (well–known)

Rosenbluth and polarisation transfer methods are incompatible in one-photon exchange (Born) approximation



2γ exchange in $ep \longrightarrow ep$, intermediate nucleon and Δ states

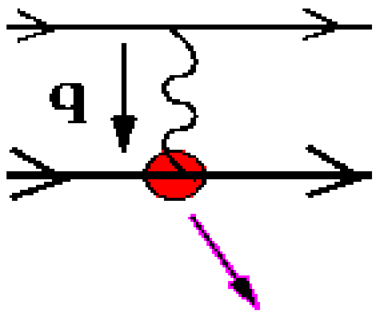
Differential cross section for $ep \longrightarrow ep$

$$d\sigma = d\sigma_{1\gamma}(1 + \delta_{2\gamma}) = |\mathcal{M}_{1\gamma} + \mathcal{M}_{2\gamma}|^2$$

2γ exchange correction:

$$\delta_{2\gamma} = 2\frac{\mathrm{Re}\left(\mathcal{M}^{\dagger}_{1\gamma}\mathcal{M}_{2\gamma}\right)}{|\mathcal{M}_{1\gamma}|^2}$$

1γ (Born) amplitude $\mathcal{M}_{1\gamma}$:



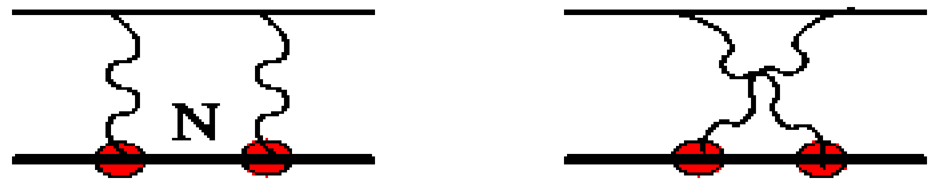
Simple tree diagram

γNN vertex:

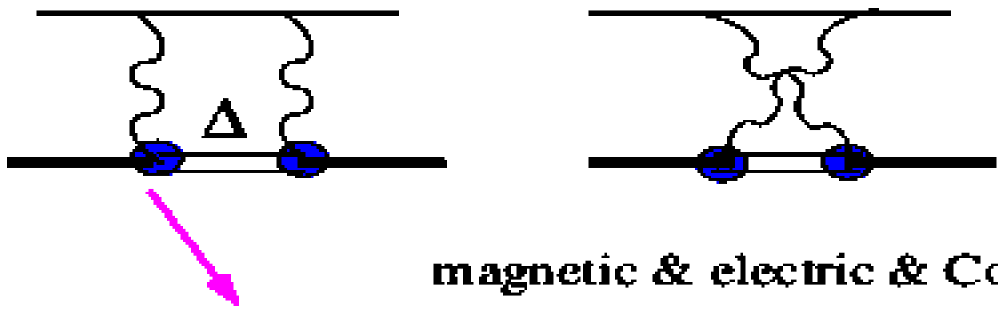
electric & magnetic components

ensures current conservation

2γ exchange amplitude $\mathcal{M}_{2\gamma} = \mathcal{M}_{2\gamma}^{N} + \mathcal{M}_{2\gamma}^{\Delta}$:



Box and crossed–box loop integrals



$\gamma N \Delta$ vertex:

magnetic & electric & Coulomb components

ensures current conservation

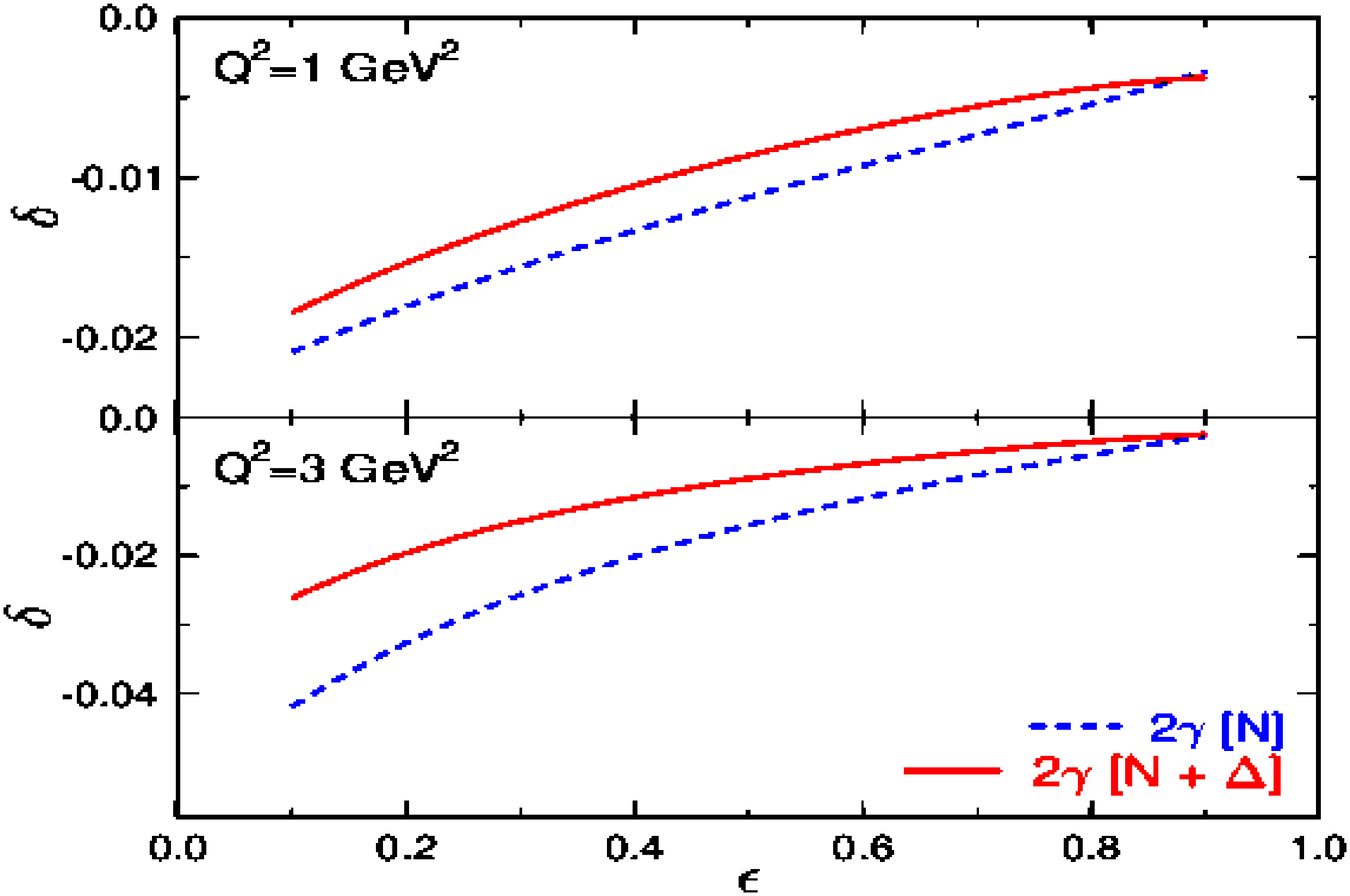
retains physical spin 3/2 Δ propagator

Loop integrals calculated explicitly

Δ is the most prominent resonance $\Rightarrow$

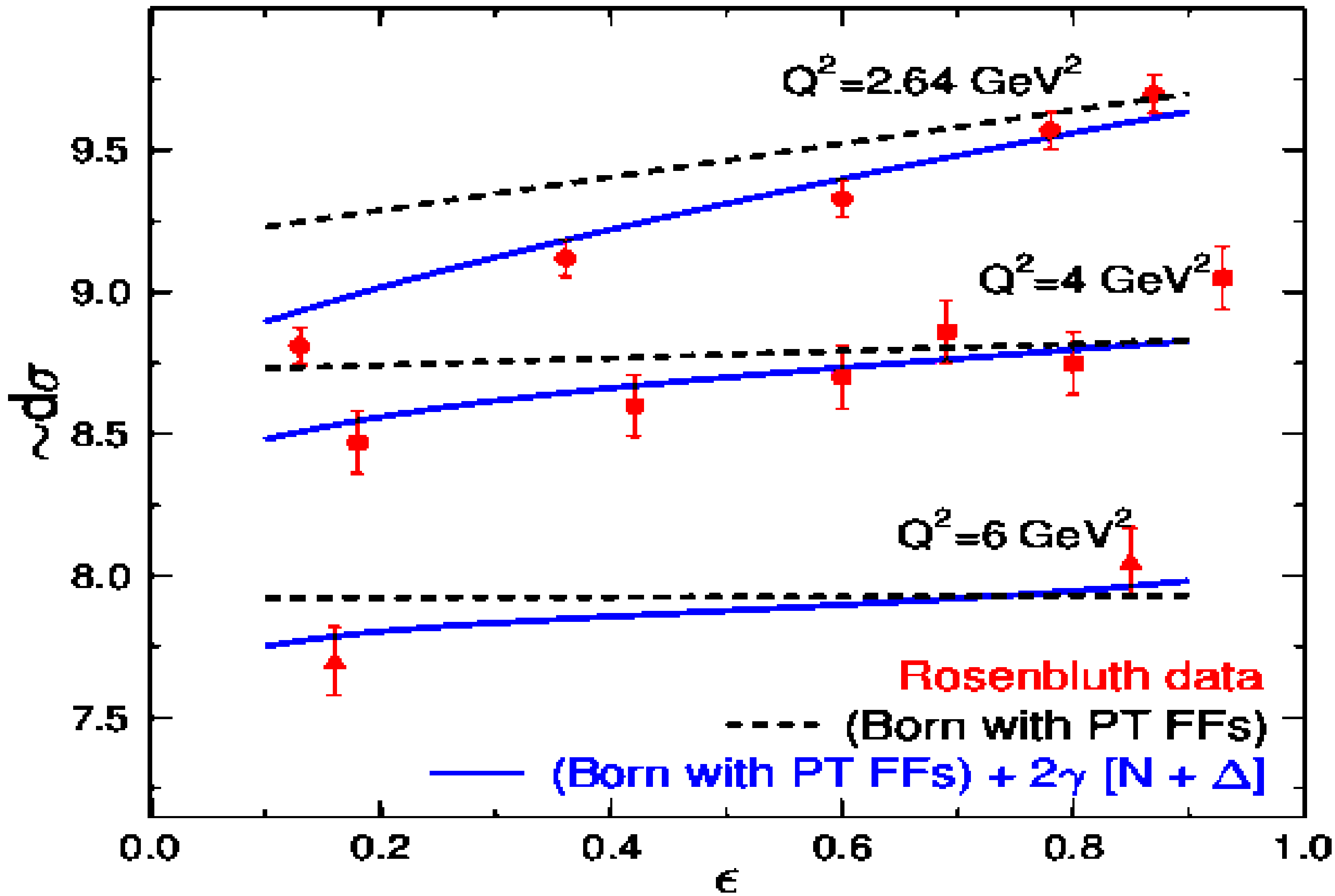
Essential to include both nucleon and Δ intermediate states

General features of the two-photon corrections:



- $\delta_{2\gamma}^{N} + \delta_{2\gamma} \approx -3\%(\theta \longrightarrow 180^{o}) \div 0\%(\theta \longrightarrow 0^{o})$
- $sign(\delta_{2\gamma}^{N}) = -sign(\delta_{2\gamma}^{\Delta})$
- $\left|\delta_{2\gamma}^{N}\right| > \left|\delta_{2\gamma}^{\Delta}\right|$
- $\left|\delta_{2\gamma}^{\Delta}(\text{magnetic})\right| > \left|\delta_{2\gamma}^{\Delta}(\text{electric})\right| > \left|\delta_{2\gamma}^{\Delta}(\text{Coulomb})\right|$

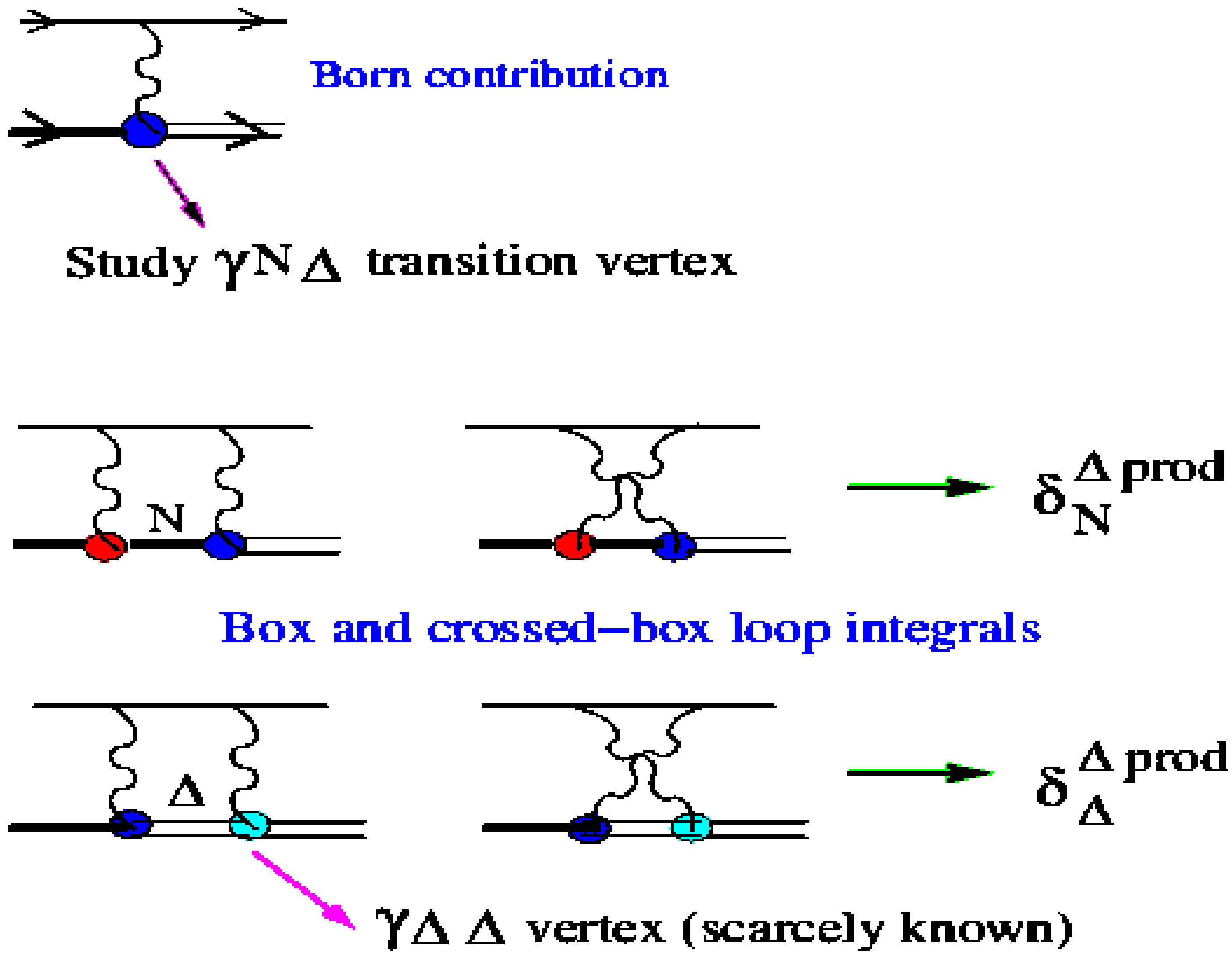
Effect of the two-photon correction on the $ep \longrightarrow ep$ cross section



Two-photon exchange corrections allow one to reconcile the Rosenbluth and polarisation transfer measurements of the nucleon form factors

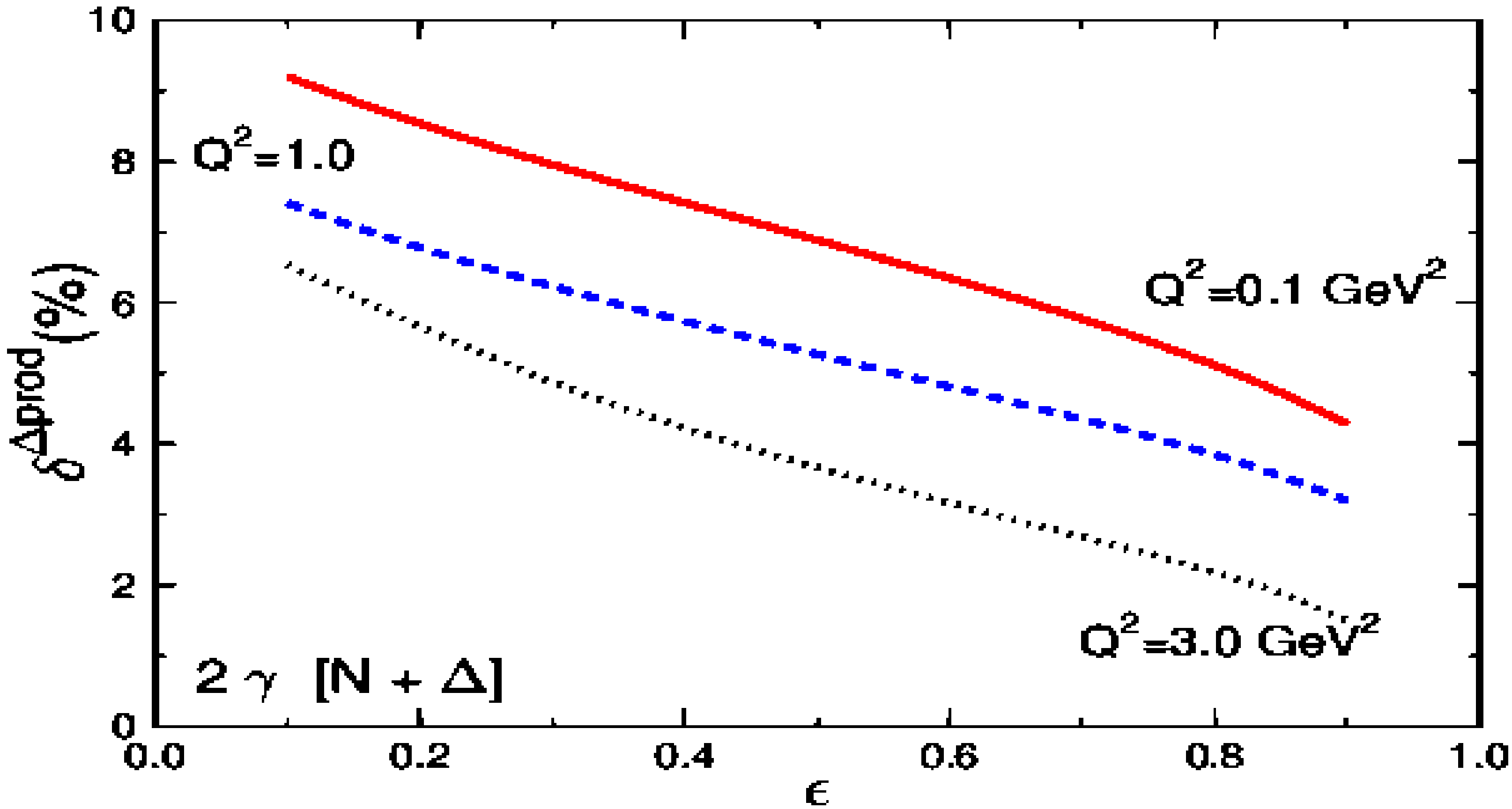
2γ exchange in $ep \to e\Delta$

- Ongoing and planned measurements of $ep \to ep\pi$ in the Δ resonance region



- Unavoidable model dependence at present

Two-photon exchange contribution to $ep \longrightarrow e\Delta$ cross section



- $\delta_N^{\Delta prod} + \delta_\Delta^{\Delta prod} \approx +8\%(\theta \longrightarrow 180^o) \div +1\%(\theta \longrightarrow 0^o)$
- $\delta_N^{\Delta prod} \sim -10\,\delta_\Delta^{\Delta prod}$
- $\delta^{\Delta prod}$ almost linear in ϵ (angle)

Conclusion

- Calculation shows that two-photon exchange is important in a theoretical description of electron-nucleon collision experiments
- Strong evidence that 2γ contribution can reconcile the Rosenbluth and polarisation measurements of nucleon e-m form factors
- Important to treat the nucleon and Δ intermediate states on the same footing (additional contributions needed at higher energies)
- Role of two-photon exchanges in inelastic ep collisions – curious preliminary results (work in progress)